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Gender Differences in NATO Anthropometry and the Implication for Protective Equipment

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14. ABSTRACT

This paper compares the body proportions of men and women from the Civilian American and European Surface Anthropometry Resource (CAESAR) project, completed in 2002, and discusses proportions that have implications for protective apparel. CAESAR was an attempt to characterize the body size and shape of the adult population of NATO countries. Four countries were surveyed: the United States of America and Canada (North America), The Netherlands, and Italy. North America was selected because it had the largest population in NATO and the most diversity. The Netherlands was selected because it had the tallest population in NATO. Italy was selected because its population was amongst the shortest.

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Summary

In the Civilian American and European Surface Anthropometry Resource (CAESAR) project men and women were sampled in approximately equal numbers making it an ideal source for understanding gender differences. Stepwise Discriminant Analyses were done using the 97 one-dimensional measurements collected in CAESAR. The results indicate an unprecedented separation of male and female body shapes. All three regions had at least 98.5% accuracy in predicting gender with seven or fewer measurements. Some important body proportion differences between men and women will impact the fit and effectiveness of many types of protective apparel such as: flight suits, anti-g suits, cold-water immersion suits, chem.-bio protective suits, etc. While women are smaller than men on average for many body measurements, women are larger than men in some important aspects. For example, women are significantly larger than men in seated hip breadth in all three populations (26 mm larger on average) while at the same time significantly smaller than men for shoulder breadth (54 mm smaller on average). CAESAR also has the advantage of providing 3D models of all subjects. This capacity was also used to provide visual comparison of subjects which is helpful for understanding the differences and deriving solutions.

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1. Introduction

Significant gender differences pervade human morphology from the chromosomal elements that dictate phenotypic expression, to the overt differences in genital structure and adipose tissue distribution. Surprisingly, one of the largest gaps in our understanding of sexual dimorphism is found in the study of gross anatomical, or anthropometric, differences. As humans, we have a qualitative understanding of anthropometric dimorphism. We use terms like ‘apple’ versus ‘pear’ shaped and we develop internal models about a male’s appearance versus a female’s. But aside from its utility with social interaction, our anecdotal experience with anthropometric gender differences is of little use. There are, however, a number of practical applications for understanding the anthropometric aspects of sexual dimorphism. One of the more obvious of these applications is the design of apparel. Although, there is a long history of gender specific clothing design, differences in men’s and women’s clothing are as much a matter of style as they are a matter of function. This may explain why certain genres of apparel such as flight-suits, chem-bio suits, and other protective garments are not generally designed with gender-based fit as a top priority. Another explanation for this oversight may center on the fact that gross anthropometric gender differences have not yet been adequately described in the literature. Without a quantitative analysis of anthropometric dimorphism, gender-specific apparel design is left to artistic interpretation instead of size and shape-based engineering.

The study of anthropometric dimorphism may also benefit the spaces in which we work. Industrial and ergonomic engineering techniques are often used to design safe and productive workstations. However, much like protective apparel, workstations are typically designed with a one-gender-fits-all approach. It is reasonable to assume that gender consideration may also improve the safety and productivity in a particular work environment. As an example, if we were to design a chair with the knowledge that females have broader hips and males have longer torsos, then we would want to build a chair with a wider seat pan and a taller seat back. To design this seat by considering only the average male, or only the average female, may compromise the fit and comfort for the other gender. While all solutions to workstation design are not expected to be as simple, this again highlights the importance of studying the gross anthropometric differences between males and females.

The benefits of understanding anthropometric gender differences have not been lost on the scientific community. There is a wealth of research addressing human sexual dimorphism from forensic and anthropological perspectives (Brown et al., 2007; King et al., 1998; Sakaue, 2004). In these fields, sexual differences are identified and quantified for purposes of post-mortem gender classification (Barrio et al., 2006; Ozer et al., 2006). As with any well-designed scientific investigation, these studies help to provide relevant solutions for the problem at hand. However, because these studies often investigate one, or a mere handful, of anthropometric measures, it is difficult to compare multiple measures. Also, it is difficult to apply such findings to apparel and workstation designs since the majority of studies involve cadaveric investigations. Anthropometric measurements from live participants allow for the comparison of skeletal structure as well as the soft tissues that surround the skeleton. Ultimately, the presence and distribution of soft tissues plays an equally critical role in safety and fit design.

In the past, there have been a number of anthropometric surveys to catalog human size and shape (Cheverud et al., 1990; Drillis & Contini, 1966). However, one common limitation has been shared by these surveys. Specifically, these studies have involved the collection of one-dimensional (1D) measurements. Measures may be presented as lengths or circumferences but they fail to capture the true size and shape of the human form. With the advent of three-dimensional (3D) scanning and other novel measurement techniques, our understanding of human morphology has expanded at an unprecedented rate. Most recently, the first 3D, multi-national anthropometric survey was completed by the United States Air Force Research Laboratories (Blackwell et al., 2002). This survey, referred to as the Civilian American and European Anthropometry Resource (CAESAR) project, reported many of the traditional 1D measurements that have classically been gathered, but it also provided a true 3D survey of human morphology. With true 3D analysis as a starting point, we are in a position to more accurately obtain many of the critical anthropometric measurements that were formerly evaluated using tape measures or calipers.

There is sufficient evidence to support the idea of sexual dimorphism at nearly every level of human anatomy. However, many of the anthropometric measures have been considered independently rather than in combination. The purpose of this investigation was to identify the anthropometric measurement combinations that best distinguish between genders in order to address issues related to apparel and workstation design and performance. The unique approach proposed in this study involves the use of anthropometric data gathered from a large population of living human participants, and the comparison of a substantial number of measures that more completely describe human size and shape.

2. Methods

2.1 Participants

Three-dimensional anthropometric data obtained from the CAESAR project were analyzed to evaluate anthropometric dimorphism in the NATO population (Blackwell et al., 2002). Specifically, the data presented in this report were gathered from a sample of nearly 4,500 participants from North America, Italy and The Netherlands. The North American population was selected for its ethnic diversity and because it provided the largest number of participants. Italy's population was selected because its citizens are among the shortest in stature. Finally, The Netherlands was selected because its population is the tallest in NATO. The gender distributions and basic demographics of the surveyed participants have been provided in Table 1.

Table 1

Basic demographics for the three NATO populations selected (mean (standard deviation)).

	North America		Italy		The Netherlands	
	males	females	males	females	males	females
gender (n)	1127	1264	412	388	565	700
stature (cm)	177.8 (7.9)	164.0 (7.3)	173.6 (6.7)	161.1 (6.2)	181.4 (9.0)	168.0 (7.6)
weight (kg)	86.2 (18.0)	68.8 (17.6)	72.7 (11.0)	57.5 (9.0)	84.0 (16.3)	72.9 (15.5)

2.2 Anthropometric Measurements

In this study, we incorporated 97 of the anthropometric measurements collected during the CAESAR project. Of these measurements, there were two different classes of data. One class included 38 measures that were gathered by hand using traditional calipers and tape measures. The other class included 59 measures that were obtained from the 3D whole body scans of each survey participant. In the later case, specific anatomical landmarks had been identified prior to scanning. Scans were then digitized to determine the relative 3D position of each landmark. Finally, distance measures were calculated between multiple 3D points.

The 97 anthropometric measures were first evaluated together to determine which combination of measures was best able to discriminate between genders (All group). The measures were also evaluated in two separate subgroups to address the specific anthropometrics that might affect both apparel and workstation design. The analysis of the two additional subgroups was important for testing only those measures that were relevant to the particular application. For example, a measure of the distance between a person's lateral humeral epicondyles (i.e. a distance between outer arms) in a resting seated position may be useful for the design of a workstation, but it is not particularly helpful for the design of coverall apparel. The first subgroup analyzed in this study represents all of the measures that may be relevant for the design of a neck-down coverall garment (ND group). Neck-down coveralls are typical of many protective work suits. The second subgroup represents all of the measures that may be considered in the design of a seated workstation (WS group). These measures involve the physical proportions that describe the extent to which an individual occupies global space.

It is important to note that the original data collection teams and equipment utilized in the CAESAR project were not the same in all countries. While the same team was used for data collections in North America and Italy, a different group of experimenters was employed to gather the survey data obtained in The Netherlands. Additionally, The Netherlands data collection team acquired 3D whole body scans using a different 3D scanner than that which was used in North America and Italy (Vitronic Vitus Pro scanner vs. Cyberware WB4 scanner, respectively).

2.3 Processing and Analysis

All data processing and analyses were performed using SAS 9.1.3 (SAS Institute Inc., Cary. NC) and NI LabVIEW 8.5 (National Instruments Corp., Austin, TX). To identify the anthropometric measures that best distinguish between genders we performed a stepwise discriminant analysis with the measures in each of the three variable groups (All, ND, and WS). Discriminant analysis was chosen for two reasons. First, discriminant analysis is well-suited for finding the combination of measures that best distinguishes between two classes of variables. Second, due to the large sample sizes in this study, standard significance testing (e.g. t-test) was expected to be significant for all comparisons of gender and population. For this same reason, the different populations were compared using Receiver Operating Characteristic (ROC) analyses instead of traditional significance testing.

For the stepwise discriminant analysis, a partial r-square threshold of 0.05 was implemented to eliminate measures that did not significantly add to the discrimination power of the discriminant function. Once all relevant measures were identified, the linear discriminant function was tested with the participants from each NATO population. Each participant was classified and the gender recognition rates for each variable group and population combination were recorded. The gender scores were also analyzed to determine the ROC area and standard error of each discriminant function (Hanley and McNeil, 1982; Wu & Wilson, 2005). ROC measures were then used to compare the classification performance between NATO populations (Hanley and McNeil, 1983).

The discriminant functions can be interpreted based upon the set of measurements that result and the magnitude of their respective coefficients. The set of measurements selected in the analysis represent the best combination for distinguishing between genders. The intercept value for body measurements can be interpreted as the contribution of overall size to the gender discriminant score. The coefficients for the measurements can be interpreted as shape or proportion differences.

3. Results

The results are broken into three sections corresponding with the three measurement sets used: 1) all, 2) neck-down coverall, and 3) workstation. This is followed by a summary of the results overall. Of the original 97 measures used as input into the analyses, only 16 showed up as significant contributors to the discriminant functions. The means and standard deviations for these 16 are listed in Table 2.

Table 2
Mean (Standard Deviation) for the anthropometric measurements identified by stepwise discriminant analysis (mm or kg).

	North America		Italy		The Netherlands	
anthropometric measure	males	females	males	females	males	females
a) waist back	481 (35)	399 (28)	468 (30)	405 (30)	475 (36)	401 (29)
b) bustpt brth	236 (27)	187 (23)	217 (20)	183 (21)	230 (25)	206 (26)
c) hip brth, sitting	382 (36)	408 (46)	359 (25)	375 (29)	382 (29)	416 (38)
d) ankle circ	269 (15)	240 (15)	263 (13)	238 (12)	267 (16)	246 (16)
e) bi-lat fem epi brth sit	463 (55)	361 (64)	449 (46)	350 (48)	427 (59)	340 (53)
f) chest circ	1040 (109)	958 (124)	958 (79)	890 (80)	1015 (102)	998 (119)
g) chest grth at scye	1055 (96)	921 (100)	978 (71)	854 (60)	1022 (85)	943 (88)
h) neck base circ	468 (30)	410 (27)	475 (21)	425 (21)	489 (36)	441 (33)
i) weight	86 (18)	69 (18)	73 (11)	58 (9)	84 (16)	73 (16)
j) triceps skinfold	13 (7)	24 (10)	13 (7)	21 (7)	10 (5)	19 (8)
k) bi-lat hum epi brth sit	561 (53)	475 (57)	557 (45)	469 (39)	562 (49)	496 (49)
l) shoulder brth	496 (36)	430 (35)	459 (27)	405 (23)	472 (29)	431 (31)
m) radiale-stylion lth rt	265 (17)	237 (15)	265 (14)	239 (14)	265 (17)	239 (16)
n) waist circ (pref)	914 (125)	789 (135)	843 (83)	752 (78)	918 (109)	845 (131)
o) knee height	562 (31)	509 (28)	541 (26)	497 (24)	558 (35)	514 (28)
p) sitting height	926 (40)	865 (36)	908 (35)	855 (30)	945 (41)	887 (38)

Note that women are larger than men on average for two of the sixteen measurements, hip breadth, sitting (c) and triceps skinfold (j). For all other measurements, including chest circumference (f), women are smaller than men. A visual index for these measurements is provided in Figure 1.

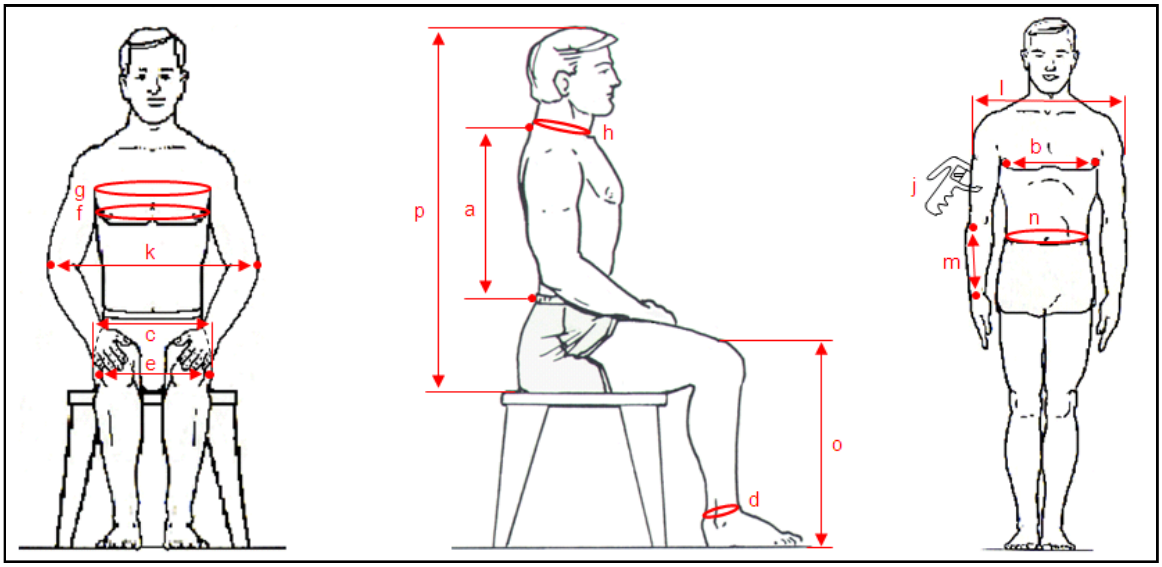

Figure 1. Anthropometric measurements identified by the stepwise discriminant analyses in each of the three test groups (letters refer to the measures in Table 2).

3.1 All Anthropometric Measures

The discriminant functions provided in Table 3 were determined for the three NATO populations based upon the incorporation of all 97 original anthropometric measures. Table 3 provides the intercept and coefficient values for the different discriminant functions determined for each population and variable group. Gender classification based upon the discriminant functions showed an accuracy of 99.5 % for North America and Italy, and 98.5% for The Netherlands (Table 4). Furthermore, the ROC areas determined for North America, Italy and The Netherlands were 0.99991, 0.99996, and 0.99754, respectively. These are all very high accuracy levels indicating that there is very small overlap between the genders. While the Dutch scores are slightly lower than the other two samples, the difference was not significant.

Application of the discriminant functions provided distinct separations of male and female gender scores in each NATO population (Figure 2). Figure 2 depicts the distribution of gender scores in each population based upon the discriminant functions derived from the all-measures groups. Gender score values greater than zero were classified as male and those less than zero were classified as female. Two curves are shown for each of the three geographic regions: North America (blue), Italy (green), and The Netherlands (red). The curve toward the left is the curve for the female subjects and the one to the right represents the distribution of the male subjects. Where the curves cross the zero point, gender has been misclassified.

Table 3
Gender discriminant functions for each of the NATO populations based on All anthropometric variables (mm or kg).

	North America	Italy	The Netherlands
intercept	-66.46	-4.50	-42.57
anthropometric measure	coefficient	coefficient	coefficient
a) waist back	0.06		0.07
b) bustpoint brth	0.16	0.12	
c) hip breadth, sitting	-0.13	-0.21	-0.11
d) ankle circumference	0.14		
e) bi-lateral femoral epicondyle brth sit	0.03	0.04	0.03
f) chest circumference	-0.08	-0.11	
g) chest girth (chest circumference at scye)	0.08	0.07	
h) neck base circumference		0.08	0.05
i) weight		0.61	
j) triceps skinfold			-0.02
k) bi-lateral humeral epicondyle brth sit			0.04

Table 4
Gender classification rate (%) and ROC area based upon the discriminant function from each variable group and population combination.

		North America	Italy	The Netherlands
All	classif. rate (%)	99.5	99.5	98.5
	ROC area	0.99991	0.99996	0.99754
ND	classif. rate (%)	98.9	99.7	99.5
	ROC area	0.9996	0.9998	0.9986
WS	classif. rate (%)	98.0	97.8	96.4
	ROC area	0.9972	0.9982	0.9943

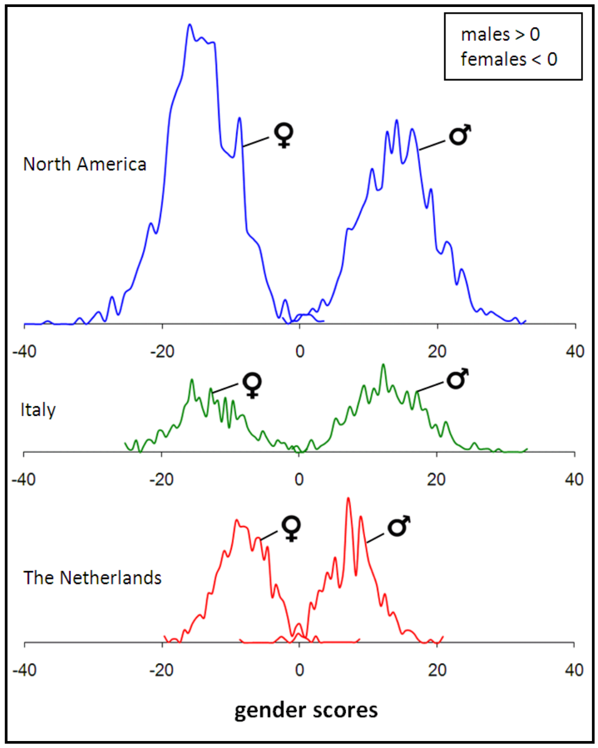

Figure 2. Gender scores calculated from the three discriminant functions from all anthropometric measures by gender and geographic region.

All three NATO samples achieved their impressive discrimination levels with seven or fewer measurements. Two measurements, hip breadth sitting and bi-lateral femoral epicondyle breadth sitting, were selected by the stepwise analysis for all three samples. This indicates they are consistently good gender discriminators. Since the former is negative and the latter is positive they represent a contrast, in this case between the hip breadth and the breadth across the knees.

The equations for the North American and Italian samples appear to represent a contrast between two measurements (hip breadth, sitting and chest circumference) and the others, even though the other measurements are slightly different. Since a negative discriminant score represents a woman and a positive score a man, this suggests that women are proportionately larger in the hips and smaller in the bi-lateral femoral epicondyle breadth sitting (outer knee to outer knee) than men, and proportionately larger in the chest circumference versus the chest circumference at scye than men. For Italy, weight (body mass) also has a large coefficient. This is an overall size measurement and accounts for the smaller intercept value for the Italian sample versus the North American.

In addition to the two measures that all three regions of the world share, the Dutch equations are similar to North America for Waist Back and similar Italy for Neck Base Circumference. The Dutch also had two unique measurements that were selected.

There was one confounding factor in the CAESAR survey that may explain some of the differences between The Netherlands and the other two populations. Namely, the anthropometric data obtained from The Netherlands was done so with a different data collection team and 3D whole body scanner (Blackwell et al., 2002). Although The Netherlands data collection team was composed of different experimenters, they were

trained in the same manner as the North American and Italian teams. It is possible that differences in 3D scanner calibration, resolution, and processing best explain the differences between The Netherlands and the other NATO populations.

In general it seems that all of the equations show a strong contrast between hip breadth and various other measures of size. This indicates that while women are smaller in most ways, they are proportionately larger in the hip than men and this is a highly distinguishing characteristic.

3.2 Neck-Down Coverall Measures

The discriminant functions provided in Table 5 were determined for the three NATO populations based upon only those anthropometric measures relevant for the design of neck-down apparel such as a flight suit or coverall. Gender classification based upon the discriminant functions was 98.9%, 99.7%, and 99.5% for North America, Italy and The Netherlands, respectively (Table 4). ROC areas determined for North America, Italy, and The Netherlands were 0.9996, 0.9998, and 0.9986, respectively. Again, these results indicate that there is little overlap between the proportions of men and women. For apparel, this means apparel proportioned for men will not be linearly scale-able to fit women (i.e. women are not scaled down men).

Table 5
Gender discriminant functions for each of the NATO populations based on the Neck-Down Coverall anthropometric variables (mm or kg).

	North America	Italy	The Netherlands
intercept	-63.09	3.78	1.13
anthropometric measure	coefficient	coefficient	coefficient
a) waist back	0.07	0.05	0.04
b) bustpoint brth	0.11	0.12	0.09
c) hip breadth, sitting	-0.12	-0.21	-0.16
l) shoulder breadth	0.08		
m) radiale-stylion len rt	0.08		
i) weight		0.64	0.29
f) chest circumference		-0.10	-0.11
g) chest girth (chest circumference at scye)		0.09	0.10
n) waist circumference (preferred)			0.02

Since fewer measurements were used the scores are slightly lower, but are still discriminating very well. Again, seven or fewer measurements contributed to the discrimination capability. In this group, there are three measurements that show up consistently regardless of sample, and again hip breadth sitting is one of them. Bustpoint breadth and waist back are the others. However, the measurement that was the other consistent measurement in the All-measures analysis, bilateral femoral epicondyle breadth sitting (the breadth from right to left outer knee), was not included in this subset because it was not deemed relevant to coveralls.

All three NATO samples' equations indicate there is a contrast or a proportional difference between men and women, and hip breadth, sitting is key to this contrast. The Italian and Dutch samples are different from the North American in that they use weight

and a contrast between chest circumference and chest girth instead of shoulder breadth and radiale-stylion length (lower arm length). However, these are all different ways of measuring overall size, body lengths and upper torso proportions. Difficulty in obtaining measurements consistently in some areas may be playing a role in the selection of measurements representing key proportional differences between men and women.

The contrast of the hip size with the other body proportions is an important issue for many apparel items including flight suits, cold water immersion suits, anti-g suits, and other protective suits because it means that a coverall or lower-body garment proportioned for men will likely not fit women. If a male proportioned suit is scaled down to fit a woman's stature, shoulder or upper chest circumference it will likely be too tight in the hips. This finding is consistent with fit testing findings for flight and anti-g suits reported by Gross et al. (2000), Robinette (1995) and Crist et al. (1995). If this is true, then unless protective equipment is specifically designed for women, women's safety for military operations could be jeopardized.

3.3 Workstation Measures

The discriminant functions provided in Table 6 were determined for the three NATO populations based upon the subset of measures relevant for the design of a seated workstation. Gender classification based upon the discriminant functions was 98%, 97.8%, and 96.4% for North America, Italy and The Netherlands, respectively (Table 4). ROC areas determined for North America, Italy, and The Netherlands were 0.9972, 0.9982, and 0.9943, respectively. Despite that limited number of measures included in the stepwise analysis of this subgroup, gender classification rates remained strong. The classification performance demonstrated by this group of measurements is also impressive given that a number of the measures are based upon posture (e.g. bi-lateral femoral epicondyle breadth sitting) rather than static anthropometric dimensions.

The two measures that were consistently selected in the All-measures analysis are also the two consistent measures for workstations. In addition, the magnitude of the intercept value also appears to be large and negative consistently. The contrast that is important for workstations is the overall size, represented by heights (sitting and knee heights) versus the hip size. A reasonable interpretation is this result is that women appear to have larger hips but shorter heights and limb lengths. This proportional difference means women will have a lower center-of-gravity which should give them an advantage for g-tolerance (provided the anti-g suit fits them) and should make control of an ejection seat easier. However, it can also mean that the control layout will have to allow for accommodation of a large hip area with a short sitting height. Robinette et al. (1998) reported this issue for the original prototype of the T-1 aircraft. An evaluation of the aircraft cockpit revealed that while 70% of white males could effectively control the aircraft, only 10% of females could do so. The females had to have the seat full-up in order to have visibility over the nose. However, with the seat full up their larger thighs and hips would not allow for full movement of the yoke in order to fly the aircraft.

Table 6
Gender discriminant functions for each of the NATO populations based on the Workstation anthropometric variables (mm or kg).

	North America	Italy	The Netherlands
intercept	-45.41	-70.20	-46.12
anthropometric measure	coefficient	coefficient	coefficient
l) shoulder breadth	0.10	0.08	
c) hip breadth, sitting	-0.13	-0.14	-0.12
e) bi-lateral femoral epicondyle brth sit	0.04	0.04	0.03
o) knee height	0.06		
p) sitting height		0.05	0.06
k) bi-lateral humeral epicondyle brth sit		0.04	0.05

3.4 Results Summary

All of the analyses indicated that there is a strong body measurement separation between men and women. Table 4 summarizes the classification rates and ROC for the three different measurement sets. All of the classification rates show greater than 96% accuracy with very high confidence.

The contrast between hip breadth and other measures of size, particularly lengths and upper torso proportions, shows up consistently in all groups. In order to visualize the discriminant logic that determined gender, the most masculine and feminine males and females from the North American population have been presented in Figure 3.

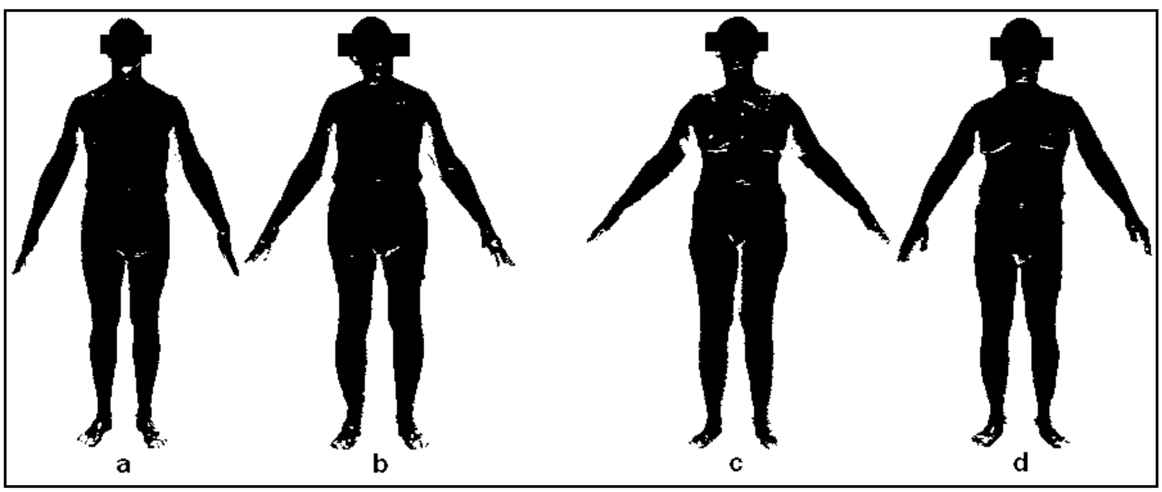

Figure 3. The most masculine and feminine male body shapes (a and b respectively) and the most feminine and masculine female body shapes (c and d respectively).

The most masculine male shape (a) clearly has a larger shoulder and upper chest proportion compared to his hip area than the most feminine male (b). The most feminine female (c) clearly has a larger hip area compared to her upper chest/shoulder area than the most masculine female (d). It also appears that the most masculine male (a) appears to have straighter (less curvy) torso than the most feminine female.

4. Summary

The results demonstrate a strong separation between men and women with all samples and measurement sets providing at least 96% accuracy in gender prediction. In addition, all regions consistently showed a strong contrast between hip breadth and other measures. This means items proportioned for men but perhaps scaled-down will not necessarily fit women and that this issue is not limited to any one country but probably exists throughout NATO.

The demonstrated contrast of the hip size with the other body proportions is an important issue for many apparel items including flight suits, cold water immersion suits, anti-g suits, and other protective suits because it means that a coverall or lower-body garment proportioned for men will likely not fit women. If a male proportioned suit is scaled down to fit a woman's stature, shoulder or upper chest circumference it will likely be too tight in the hips. This means if protective equipment is not specifically designed for women, women's safety for military operations could be jeopardized.

The larger hip size in women accompanied by the smaller sizes in most other areas including heights and lengths is also important for workstations and seats. It means women will have a lower center-of-gravity than men which should give them an advantage for g-tolerance (provided the anti-g suit fits them) and should make control of an ejection seat easier. However, it can also mean that the control layout will have to allow for accommodation of a large hip area with a short sitting height.

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